

## Circulation in southern Lake Michigan during winter season and during northerly storm episodes

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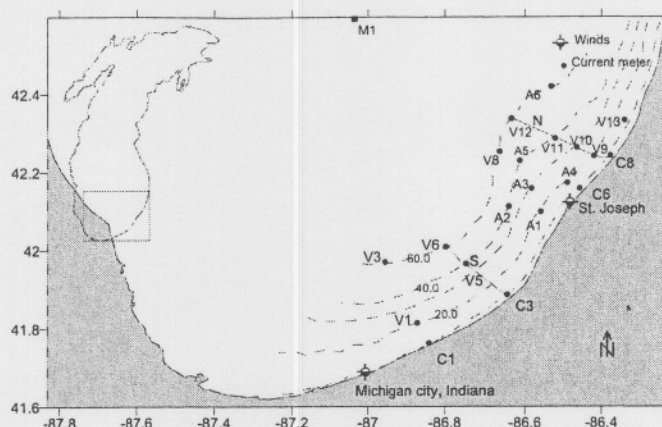
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### Introduction

Satellite imagery from early 1996 captured the initiation, development, and decay of a recurrent coastal plume in southern Lake Michigan (Eadie *et al.* 1996). A 10 km wide plume of resuspended material extending over 100 km along the southern shore of Lake Michigan coincided with the disappearance of the ice in the southern basin in late March, and with occurrence of a major storm with strong northerly winds. Circulation in the lakes is driven by wind, but the effects of earth's rotation, basin topography, and vertical density structure are also important. During the unstratified season, the higher wind speeds and the absence of the thermocline allow the effects of wind action to penetrate deeper into the water column. In shallow water the entire water mass moves in the direction of the wind, while return flow occurs in the deeper parts of the lake with a relatively uniform over-lake wind field. This forms two counter-rotating closed gyres, a cyclonic gyre to the right of the wind and an anticyclonic gyre to the left (Saylor *et al.* 1980). These rotary motions or vorticity waves have been suggested as one of the important mechanisms for nearshore-offshore transport in the Great Lakes. In order to understand the cross-shore transport of material and quantify the physical processes that are responsible for the nearshore-offshore mass exchange, a multidisciplinary research program, EEGLE (Episodic Events Great Lakes Experiment) was initiated in Lake Michigan by US National Science Foundation (NSF) and National Oceanic and Atmospheric Administration (NOAA).



*Fig. 1. Map showing bathymetry and moored instrumentation details during EEGLE.*

### Materials and methods

The observational strategy for obtaining the cross-shore and alongshore currents, physical environment, and temperature consisted of three components: (a) moored instruments (b) Lagrangian measurements and (c) ship-board surveys. In the moored instrumentation time series of currents, winds, and temperature data were obtained for the field years of 1997 to 2000. A maximum of 17 moorings of Acoustic Doppler Current Profilers (ADCP) and Vector Averaging Current Meters (VACM) were deployed from the 20 m to 60 m depth contours by the NOAA Great Lakes Environmental Research Laboratory. As a part of the program National Water Research Institute deployed additional instrumentation consisting of seven Smart Acoustic Current Meters (SACM), and two ADCPs in shallow waters at a depth of 12 m along with two coastal meteorological stations installed on piers at Michigan city, Indiana and St. Joseph, Michigan (Fig. 1). In this paper we study the circulation during the winter season and three northerly storm episodes.

### Results and discussion

#### Winter circulation

Wind driven transport is the dominant feature of the circulation in the lakes. The spatial and temporal variability of wind field can have considerable influence on the circulation pattern in the coastal zones. As an example the

surface wind stress computed at St. Joseph station by the drag formula of Wu (1980) is presented in Fig. 2. Time series of wind stress during three winters shows the winds are variable roughly at 3–4 day periodicity. The currents in general follow the winds in the coastal region. The alongshore currents are dominant at all the stations, and cross-shore velocities account for less than 30–40 % of all sub-surface current flow. Figure 3 shows the mean currents during the winter season of 2000. The net seasonal currents during the winter are directed towards the north. The mean alongshore currents increased offshore, whereas cross-shore currents exhibited onshore flow in the coastal region, with much stronger offshore flow occurring at the deeper stations. The mean currents show similar structure throughout the water column indicating the barotropic nature of the currents during the season. The cross-shore flow may also be associated with the Ekman veering of bottom boundary layer currents. Off southeastern shore of Lake Michigan the observed net northward longshore currents can produce an offshore component to flow near the bottom. The veering of the velocity vector in an anti-clockwise direction is observed at several stations. The veering angle varied by nearly  $8\text{--}10^\circ$  from 1 m above bottom to 11 m below the surface.

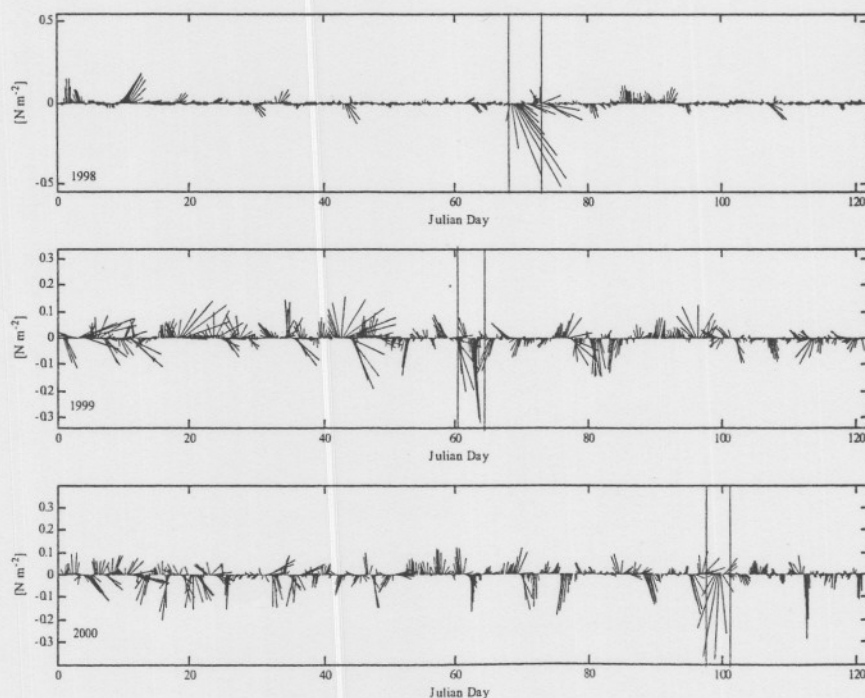


Fig. 2. Wind stress vectors at St. Joseph during three field years.



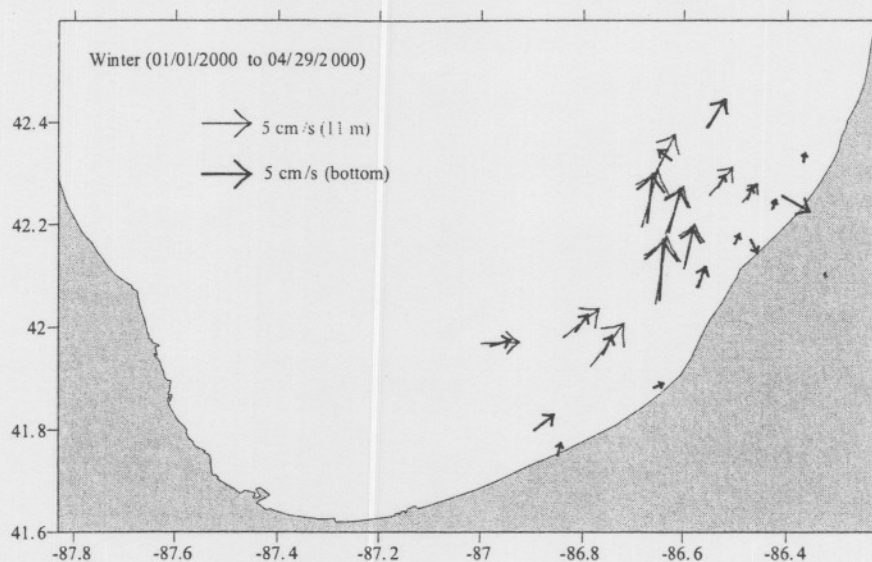


Fig. 3. Mean winter currents in southern Lake Michigan from 2000 observations (grey arrows show surface 11 m flow, and black arrows show bottom currents).

#### Influence of northerly storms

In order to analyze the variability of circulation during storm episodes three northerly storm episodes have been selected in each field year. During the first event (March 9–12, 1988) the winds were as high as  $19\text{--}20\text{ m s}^{-1}$  ( $\sim 0.5\text{ N m}^{-2}$ ) and blew towards south-east (Fig. 2). During this episode nine moorings returned good quality data. The depth-averaged currents were calculated from these nine current meter moorings (Fig. 4a). In general the offshore currents are stronger and flowed in northward direction, and under the influence of storm forced winds the nearshore currents flowed in southward direction. During the 1999 northerly storm event (March 2–5, 1999) the maximum wind stress was  $0.3\text{ N m}^{-2}$  and directed towards south. During this episode several current meter moorings provided high quality data, and the depth-averaged currents show southward currents to the north of St. Joseph, and northward currents to the south of St. Joseph (Fig. 4b). This indicates that two-gyre circulation is a major mechanism for offshore transport during this episode. During April 8 to 10, 2000 storm episode, the strong northerly winds ( $\sim 0.35\text{ N m}^{-2}$ ) reversed the currents in the shallow region. The net depth-averaged currents showed onshore transport in shallow regions to the south

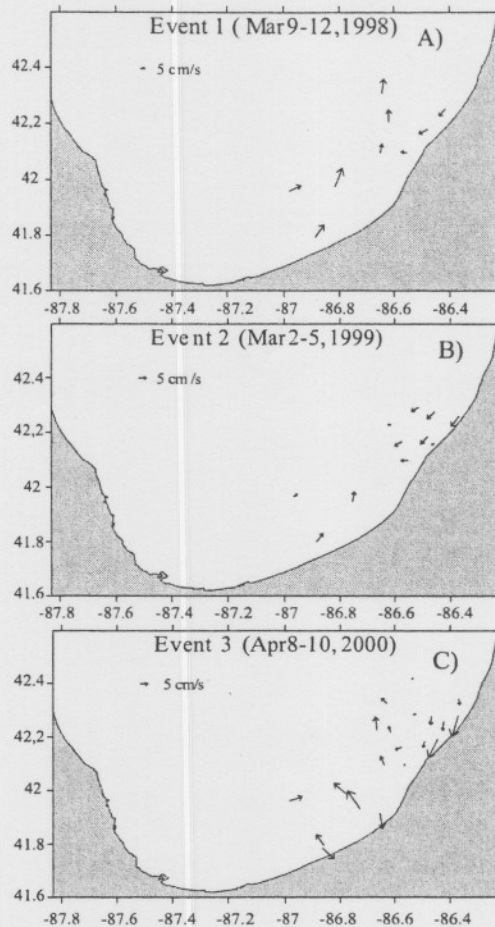


Fig. 4. Depth-averaged currents during three northerly storm episodes in southern Lake Michigan.

of St. Joseph, and offshore transport in deeper waters. During this episode the offshore transport increased marginally at mid-depth stations, whereas in the southern stations the offshore transport is significant. Once the storm had withdrawn the currents flowed in northward direction approximately at a period of 4 days (Rao *et al.* 2002).

### Conclusions

The winter currents in southern Lake Michigan are barotropic and exhibit fluctuations at 3–5 day period. The net seasonal currents during the winter season flow predominantly in alongshore direction and are directed towards

north. The cross-shore flow is also associated with Ekman veering of bottom boundary layer currents. During northerly storm episodes the mean current speeds increased significantly and the coastal currents flowed in the opposite direction under the direct influence of prevailing winds. The offshore currents in general flowed towards north. The cross-shore and alongshore transports showed opposite trends from mean winter to storm episodes. Furthermore, these observations suggest that the combination of directly wind forced currents in the coastal region and the free wave response in deeper waters could be a source of offshore transport.

#### References

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